

# Unitarity Triangle and New Physics

Enrico Lunghi  
University of Indiana

Brookhaven Forum 2008

Based on: E.L. and A. Soni, arXiv:0707.0212  
arXiv:0803.4340  
in preparation

# Outline

- A critical review of the UT fit:
  - New formula for  $\varepsilon_K$  [Andriyash, Ovanesyan, Vysotsky]  
[Buras, Guadagnoli]
  - The role of  $V_{cb}$  and  $V_{ub}$
  - Updated inputs
- The UT fit and what it suggests about new physics:
  - NP in  $B_d$  mixing and in  $b \rightarrow s$  amplitudes [EL, Soni]
  - NP in  $K$  mixing and in  $b \rightarrow s$  amplitudes [Buras, Guadagnoli]  
[EL, Soni]
- Operator Analysis of New Physics effects [EL, Soni]
- Conclusions

# K mixing

$$\begin{aligned}\varepsilon_K &= \frac{A(K_L \rightarrow (\pi\pi)_{I=0})}{A(K_S \rightarrow (\pi\pi)_{I=0})} \\ &= e^{i\phi_\varepsilon} \sin \phi_\varepsilon \left( \frac{\text{Im} M_{12}^K}{\Delta M_K} + \frac{\text{Im} A_0}{\text{Re} A_0} \right) \\ &= e^{i\phi_\varepsilon} \kappa_\varepsilon C_\varepsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \eta \left( |V_{cb}|^2 (1 - \bar{\rho}) + \eta_{tt} S_0(x_t) \right. \\ &\quad \left. + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \right)\end{aligned}$$

- Experimentally one has:  $\phi_\varepsilon = (43.51 \pm 0.05)^\circ$  [PDG]
- $\text{Im} A_0 / \text{Re} A_0$  can be extracted from experimental data on  $\varepsilon'/\varepsilon$  and theoretical calculation of isospin breaking corrections
- The final result is:  $\kappa_\varepsilon = 0.92 \pm 0.02$  [Andryash, Ovanesyan, Vysotsky; Nierste; Buras, Jamin; Bardeen, Buras, Gerard; Buras, Guadagnoli]

# K mixing

$$|\varepsilon_K| = \kappa_\varepsilon C_\varepsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \eta \left( |V_{cb}|^2 (1 - \bar{\rho}) + \eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \right)$$

- Note the quartic dependence on  $V_{cb}$ :  $|V_{cb}|^4 \sim A^4 \lambda^8$
- Critical input from lattice QCD:

$$\langle K^0 | \mathcal{O}_{VV+AA}(\mu) | \bar{K}^0 \rangle = \frac{8}{3} f_K^2 M_K^2 B_K(\mu)$$

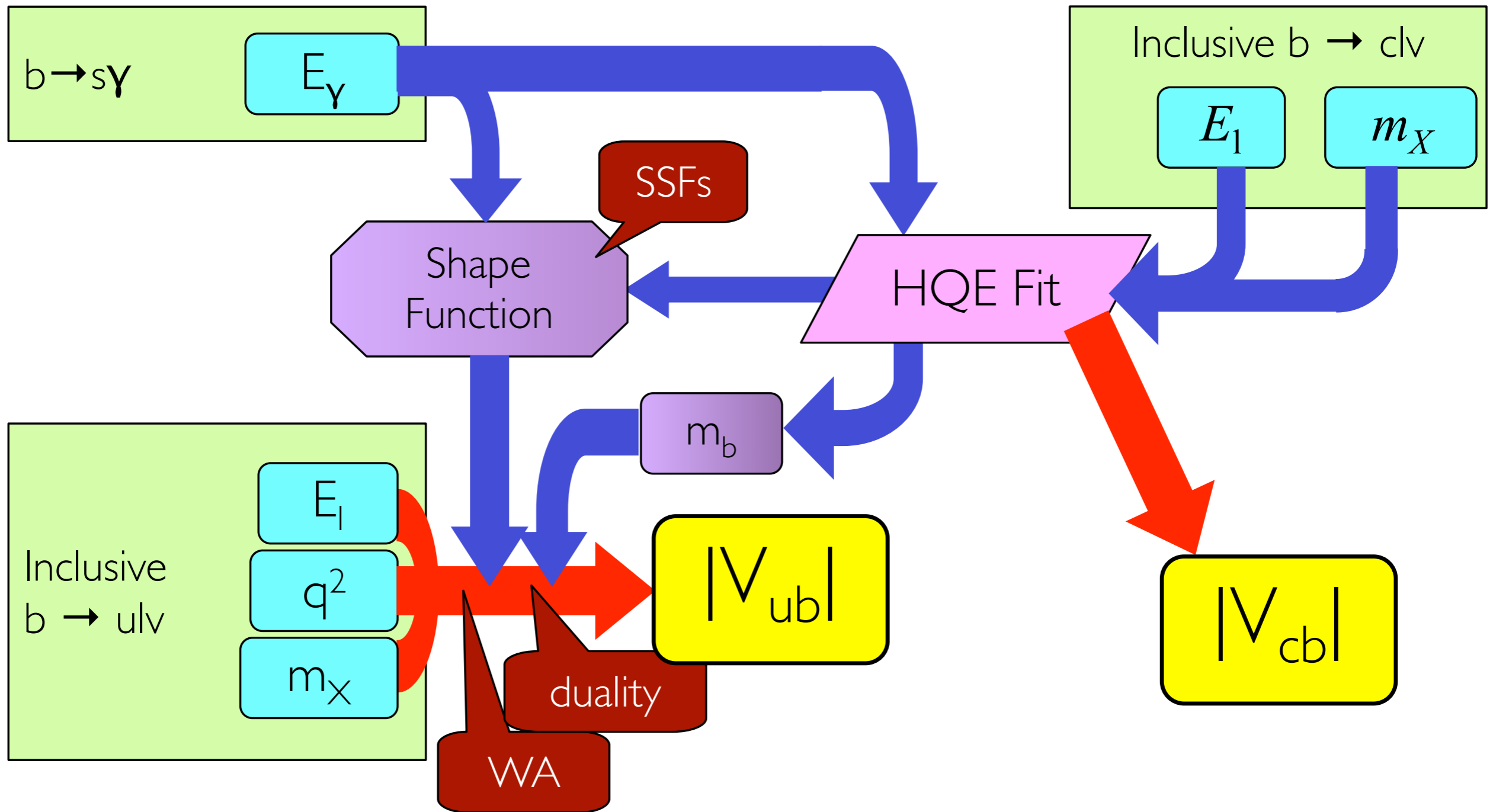
Using 2+1 flavor domain wall fermions, the RBC and UKQCD collaborations find [PRL'08]:

$$B_K^{\overline{MS}}(2\text{GeV}) = Z_{B_K}^{\overline{MS}} B_K = [0.928(05)_{\text{stat}}(23)_{\text{disc}}] \times \\ \times [0.565(10)_{\text{stat}}(06)_{\text{FVE}}(11)_{\text{Ch}}(06)_{m_s}(23)_{\text{scale}}]$$

Adding the systematic errors in quadrature they quote:

$$\hat{B}_K = 0.720 \pm 0.013_{\text{stat}} \pm 0.037_{\text{syst}}$$

# Interplay between $b \rightarrow s\gamma$ , $V_{cb}$ and $V_{ub}$



[Phillip Urquijo]

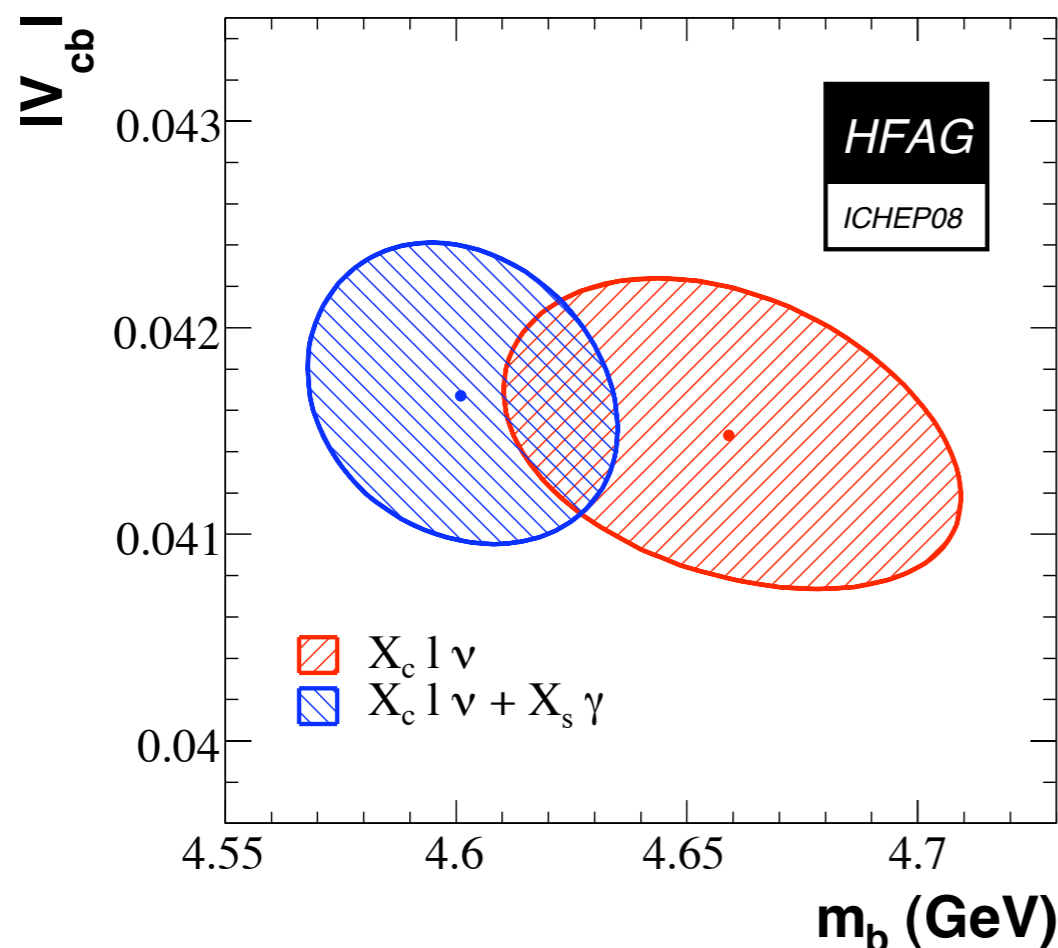
- **Exclusive from  $B \rightarrow D^* l \nu$ .** Using form factor from lattice QCD (2+1 dynamical staggered fermions) one finds:

$$|V_{cb}| = (38.7 \pm 0.9_{\text{stat}} \pm 1.0_{\text{syst}}) 10^{-3}$$

[Laiho]

- **Inclusive from global fit of  $B \rightarrow X_c l \nu$  moments.**

[Büchmüller, Flächer]



- Inclusion of  $b \rightarrow s \gamma$  has strong impact on quark masses but not on  $V_{cb}$
- NNLO in  $\alpha_s$  and  $O(1/m_b^4)$  known
- Calculation of  $O(\alpha_s/m_b^2)$  under way
- Issue of  $m_b$  is relevant for  $V_{ub}$

$$|V_{cb}| = (41.67 \pm 0.43 \pm 0.08 \pm 0.58) 10^{-3}$$

**1.9 $\sigma$  discrepancy between inclusive and exclusive**

- **Exclusive from  $B \rightarrow \pi l \nu$ .** Using form factor from lattice QCD (2+1 dynamical staggered fermions) one finds:

$$|V_{ub}| = (2.94 \pm 0.35) 10^{-4}$$

[preliminary Fermilab/Milc:  
Van de Water @ Lattice 08]

- **Inclusive from global fit of  $B \rightarrow X_u l \nu$  moments.**

$$|V_{ub}| = (3.96 \pm 0.15_{\text{exp}}^{+0.20}_{-0.23\text{th}}) 10^{-3}$$

[Gambino, Giordano, Ossola,  
Uraltsev (GGOU)]

$$|V_{ub}| = (4.26 \pm 0.14_{\text{exp}}^{+0.19}_{-0.13\text{th}}) 10^{-3}$$

[Andersen, Gardi (DGE)]

$$|V_{ub}| = (4.32 \pm 0.16_{\text{exp}}^{+0.32}_{-0.27\text{th}}) 10^{-3}$$

[Bosch, Lange, Neubert, Paz  
(BLNP)]

**2.3 $\sigma$  discrepancy between inclusive and exclusive**

# B<sub>q</sub> mixing

- We consider the ratio of the B<sub>s</sub> and B<sub>d</sub> mass differences:

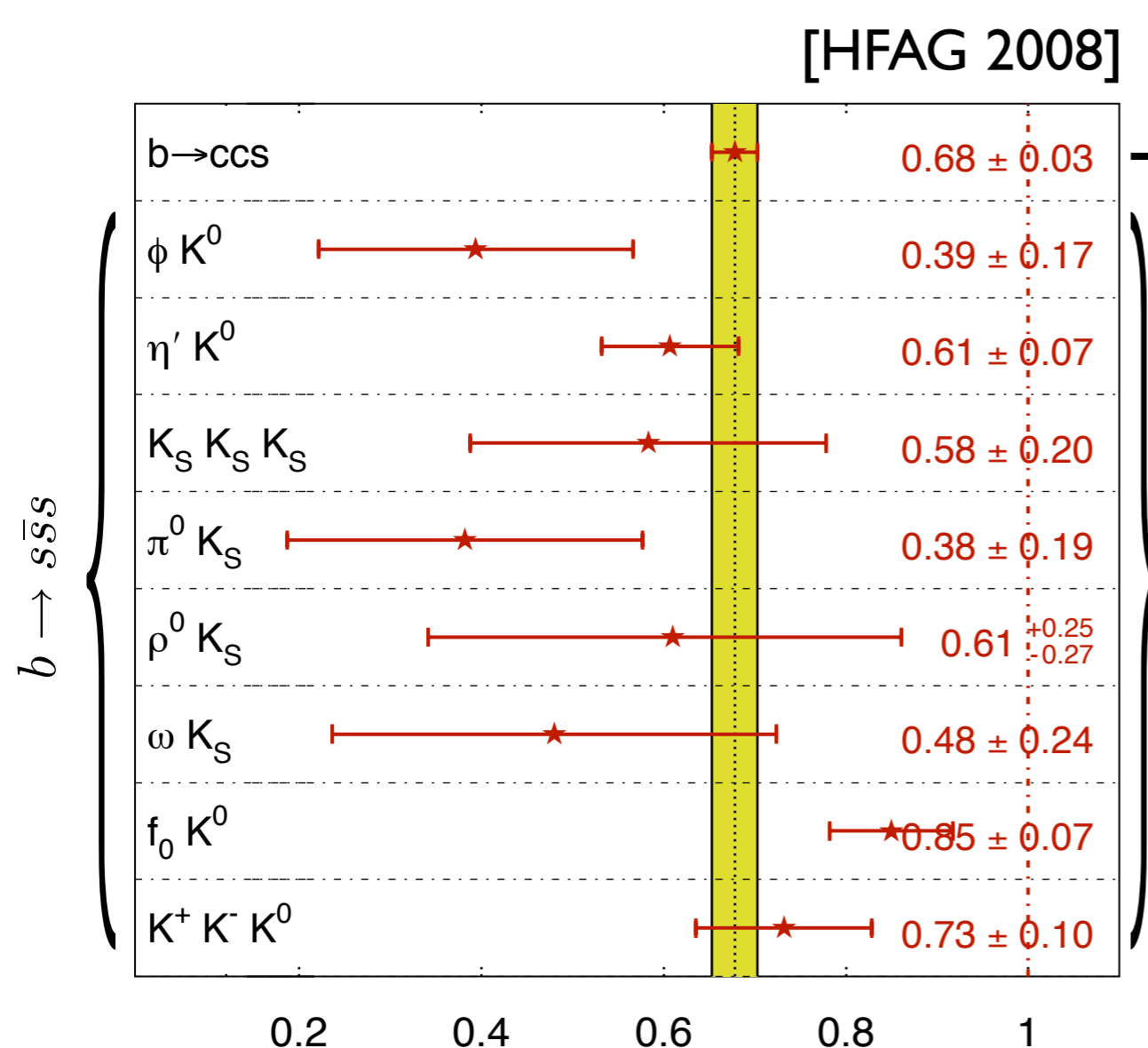
$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \frac{m_{B_s}}{m_{B_d}} \frac{\hat{B}_s f_{B_s}^2}{\hat{B}_d f_{B_d}^2} \left| \frac{V_{ts}}{V_{td}} \right|^2 = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

- No dependence on V<sub>cb</sub>
- Using 2+1 flavor staggered fermions, the Fermilab lattice and MILC collaborations find:

$$\xi = 1.211 \pm 0.045$$

- Compatible with previous partially unquenched results:  
 $\xi = 1.20 \pm 0.06$  [Fermilab/MILC, HPQCD, Becirevic]

# $\sin(2\beta)$



$$\rightarrow a_{\psi K_S} = \sin(2\beta) + O(0.1\%)$$

In QCDF:

$$\Delta a_f \equiv a_f - \sin 2(\beta + \theta_d)$$

$$= 2 \left| \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \right| \cos 2\beta \sin \gamma \operatorname{Re} \left( \frac{a_f^u}{a_f^c} \right)$$

**0.025**

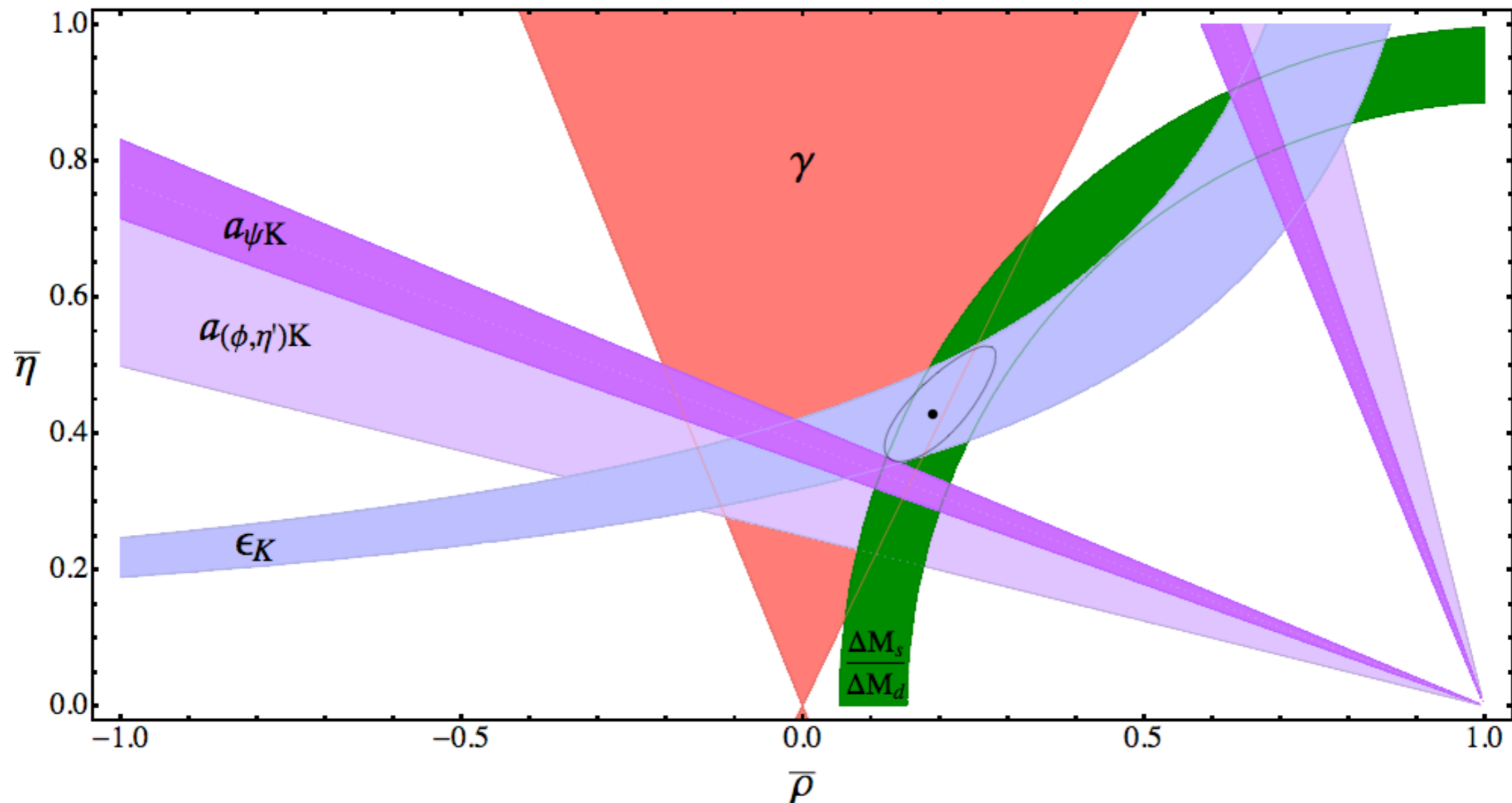
$$\Delta a_\phi = 0.03 \pm 0.01 \quad [\text{Beneke, Neubert}]$$

$$\Delta a_{\eta'} = 0.01 \pm 0.025 \quad [\text{EL, Soni}]$$

Other approaches find similar results  
[Chen, Chua, Soni; Buchalla, Hiller, Nir, Raz]

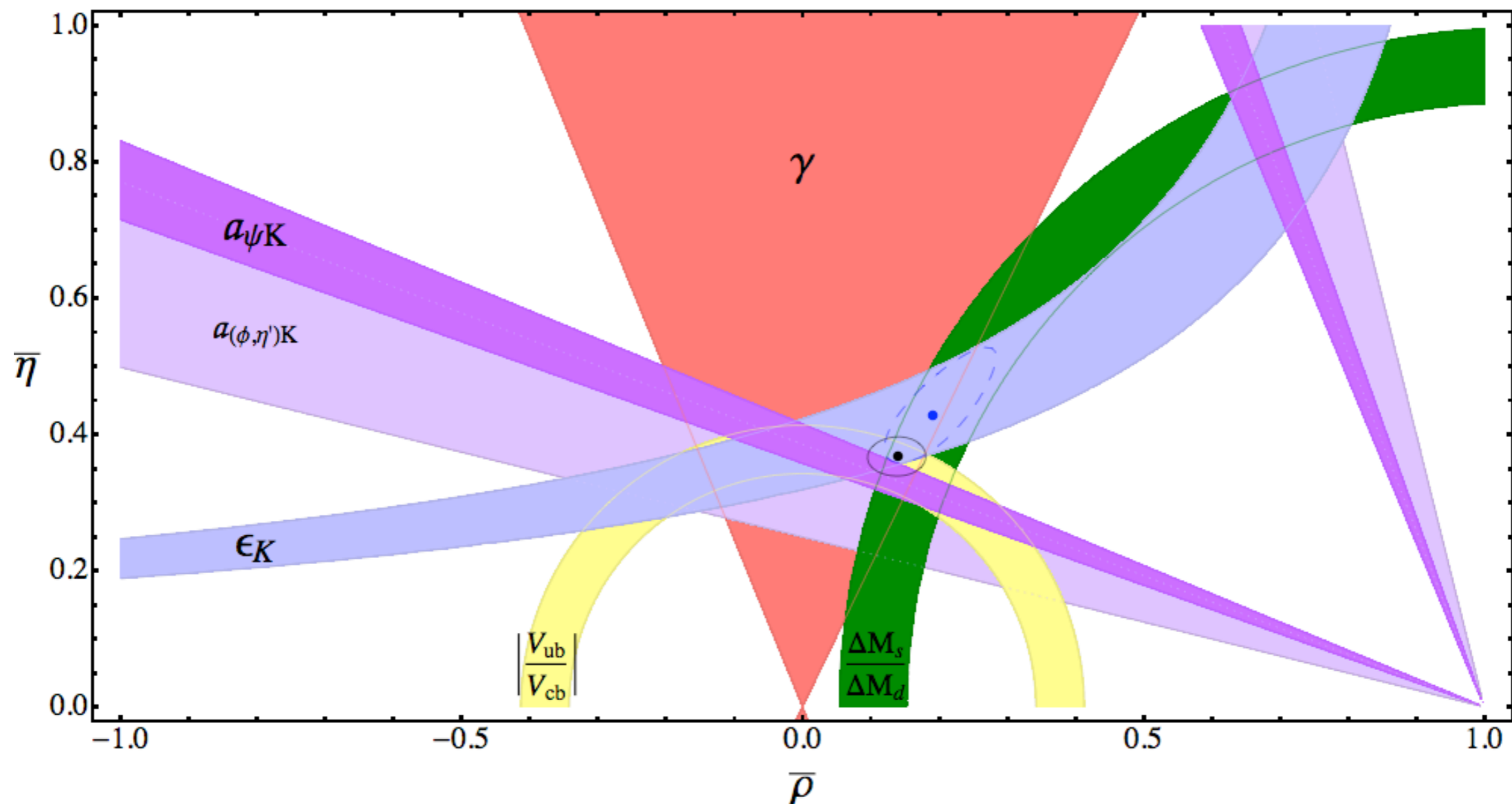
- We will consider the asymmetries in the  $J/\psi$ ,  $\phi$ ,  $\eta'$  modes
- A case can be made for the  $K_S K_S K_S$  final state [Cheng, Chua, Soni]

# Problem statement



- $\epsilon_K + \Delta M_{Bs}/\Delta M_{Bd} + V_{cb} + \gamma : \sin(2\beta) = 0.83 \pm 0.08$   
 $a_{\psi K} = 0.671 \pm 0.024$  [1.9  $\sigma$ ]  
 $a_{\phi K} = 0.44^{+0.17}_{-0.18}$  [2.0  $\sigma$ ]  
 $a_{\eta' K} = 0.59 \pm 0.07$  [2.2  $\sigma$ ]

# Problem statement



- $\epsilon_K + \Delta M_{B_s}/\Delta M_{B_d} + V_{cb} + \gamma + V_{ub}$ :  $\sin(2\beta) = 0.72 \pm 0.03$
- $a_{\psi K} = 0.671 \pm 0.024$  [1.3  $\sigma$ ]
- $a_{\phi K} = 0.44^{+0.17}_{-0.18}$  [1.6  $\sigma$ ]
- $a_{\eta' K} = 0.59 \pm 0.07$  [1.7  $\sigma$ ]

# Model Independent Interpretation

- The tension in the UT fit can be interpreted as evidence for new physics contributions to  $\varepsilon_K$  and to the phases of  $B_d$  mixing and of  $b \rightarrow s$  amplitudes:

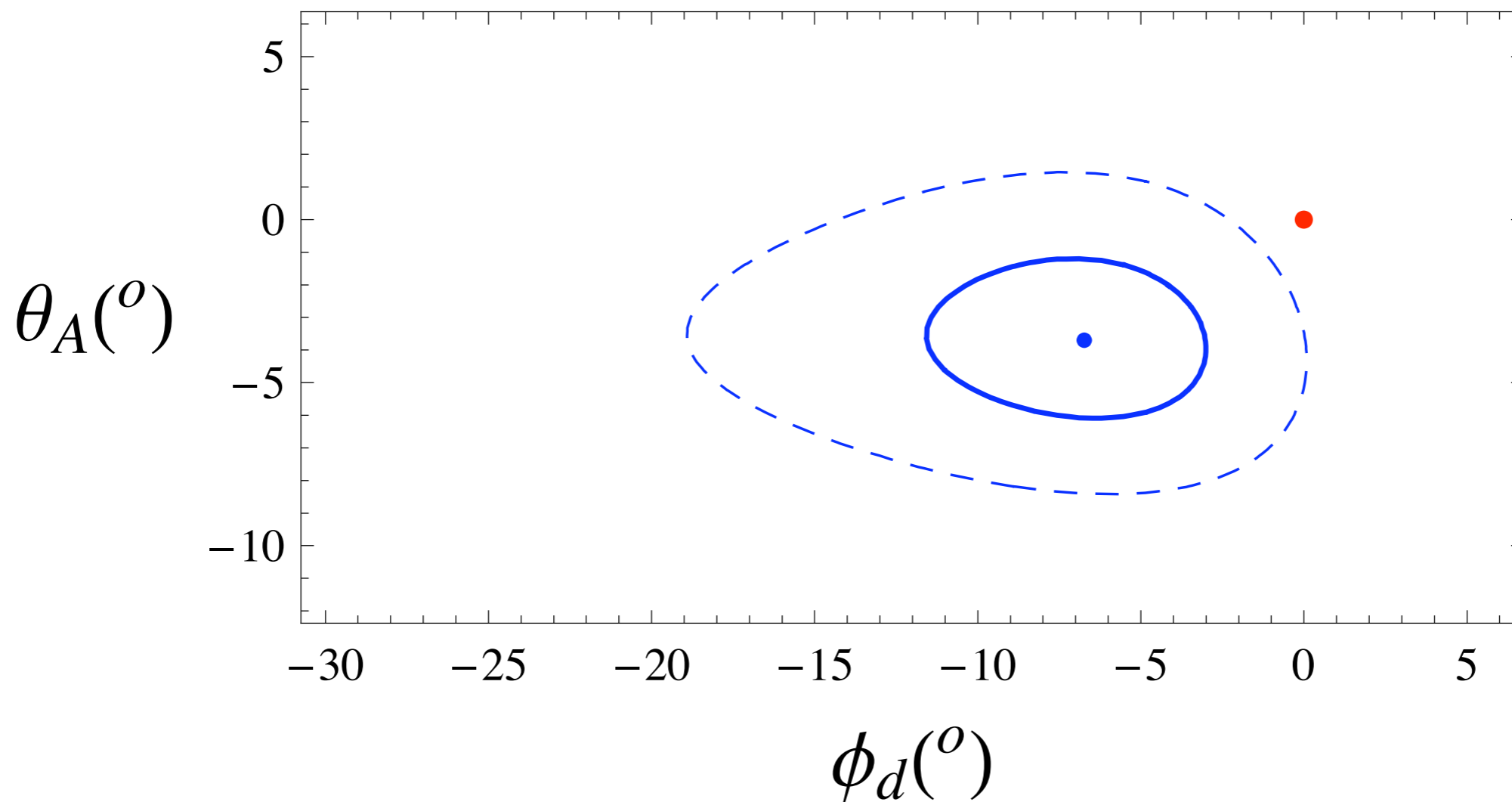
$$\begin{aligned}\varepsilon_K &= \varepsilon_K^{\text{SM}} C_\varepsilon \\ M_{12} &= M_{12}^{\text{SM}} e^{2i\phi_d} \\ A(b \rightarrow s\bar{s}s) &= [A(b \rightarrow s\bar{s}s)]_{\text{SM}} e^{i\theta_A}\end{aligned}$$

- This implies:  $a_{\psi K_s} = \sin 2(\beta + \phi_d)$   
 $a_{(\phi, \eta') K_s} = \sin 2(\beta + \phi_d + \theta_A)$

- In general NP will affect in different ways the various  $b \rightarrow s$  channels [*I will discuss this possibility in the operator level analysis*]

# Model Independent Analysis: $B_d$

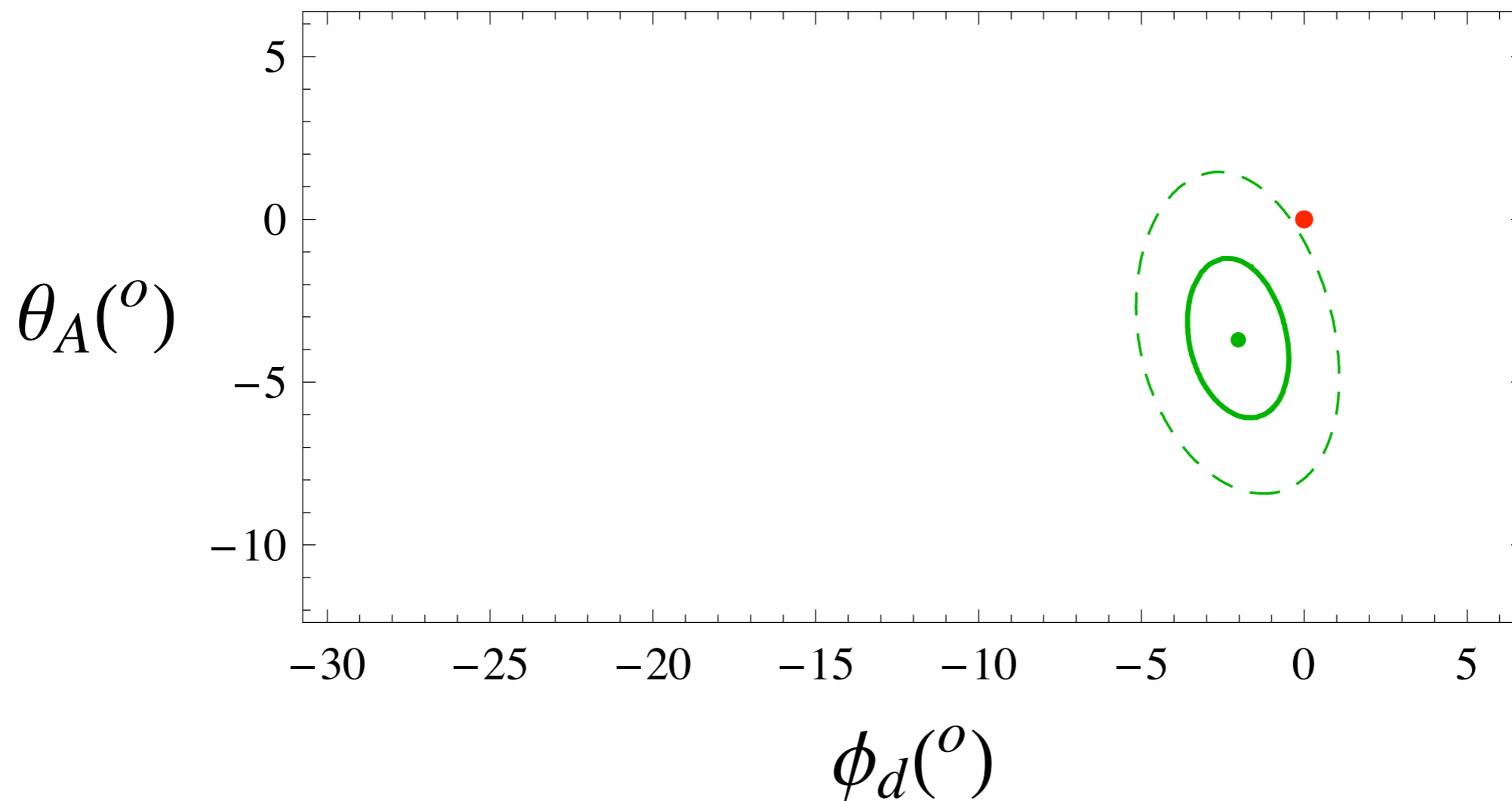
- Assume  $C_\varepsilon = 1$



- Without  $V_{ub}$ :  
 $\phi_d = (-7.3 \pm 4.3)^\circ$   
 $\theta_A = (-3.6 \pm 2.5)^\circ$

# Model Independent Analysis: $B_d$

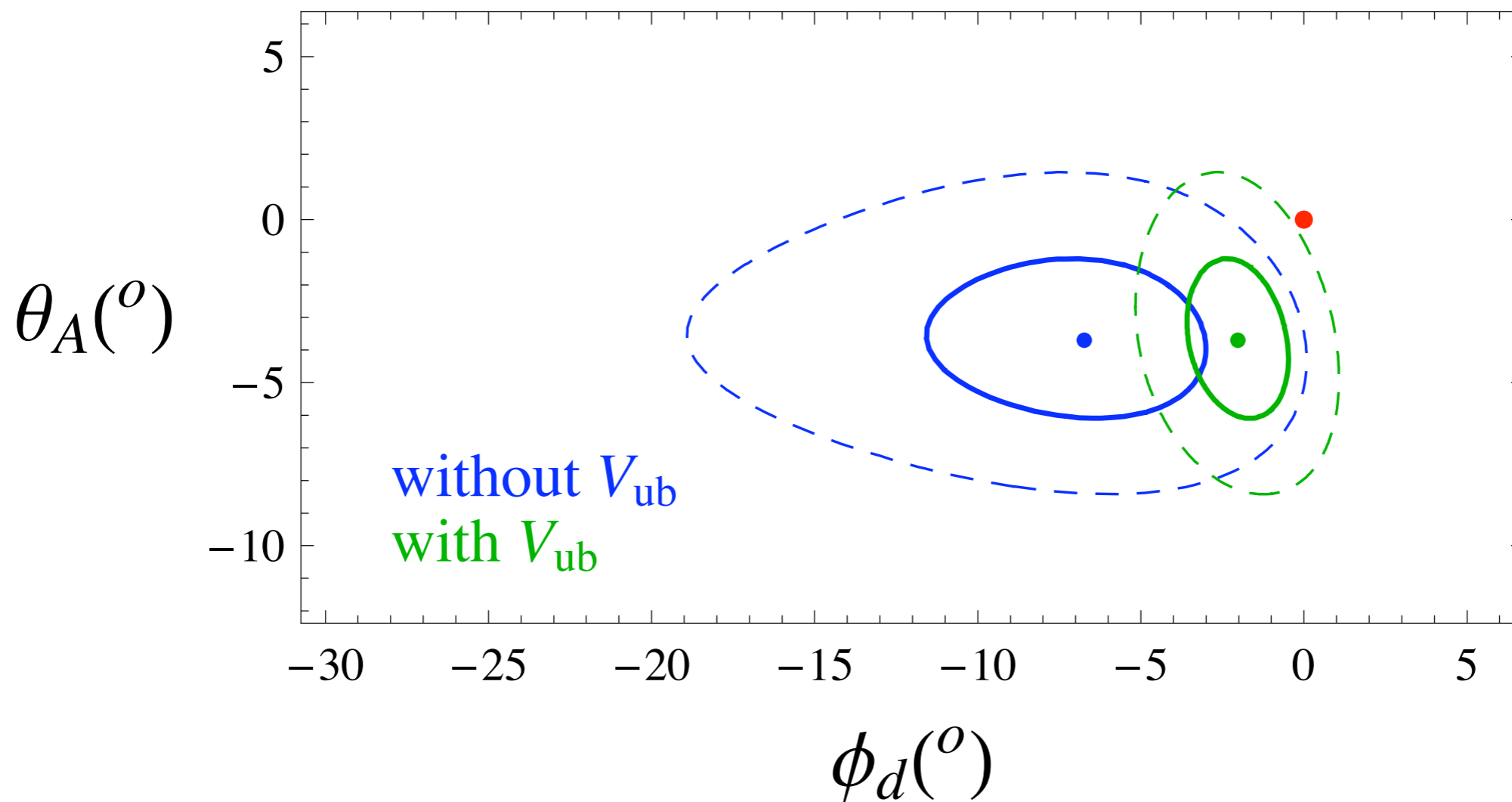
- Assume  $C_\varepsilon = 1$



- With  $V_{ub}$ :  $\phi_d = (-2.0 \pm 1.6)^\circ$   
 $\theta_A = (-3.6 \pm 2.5)^\circ$

# Model Independent Analysis: $B_d$

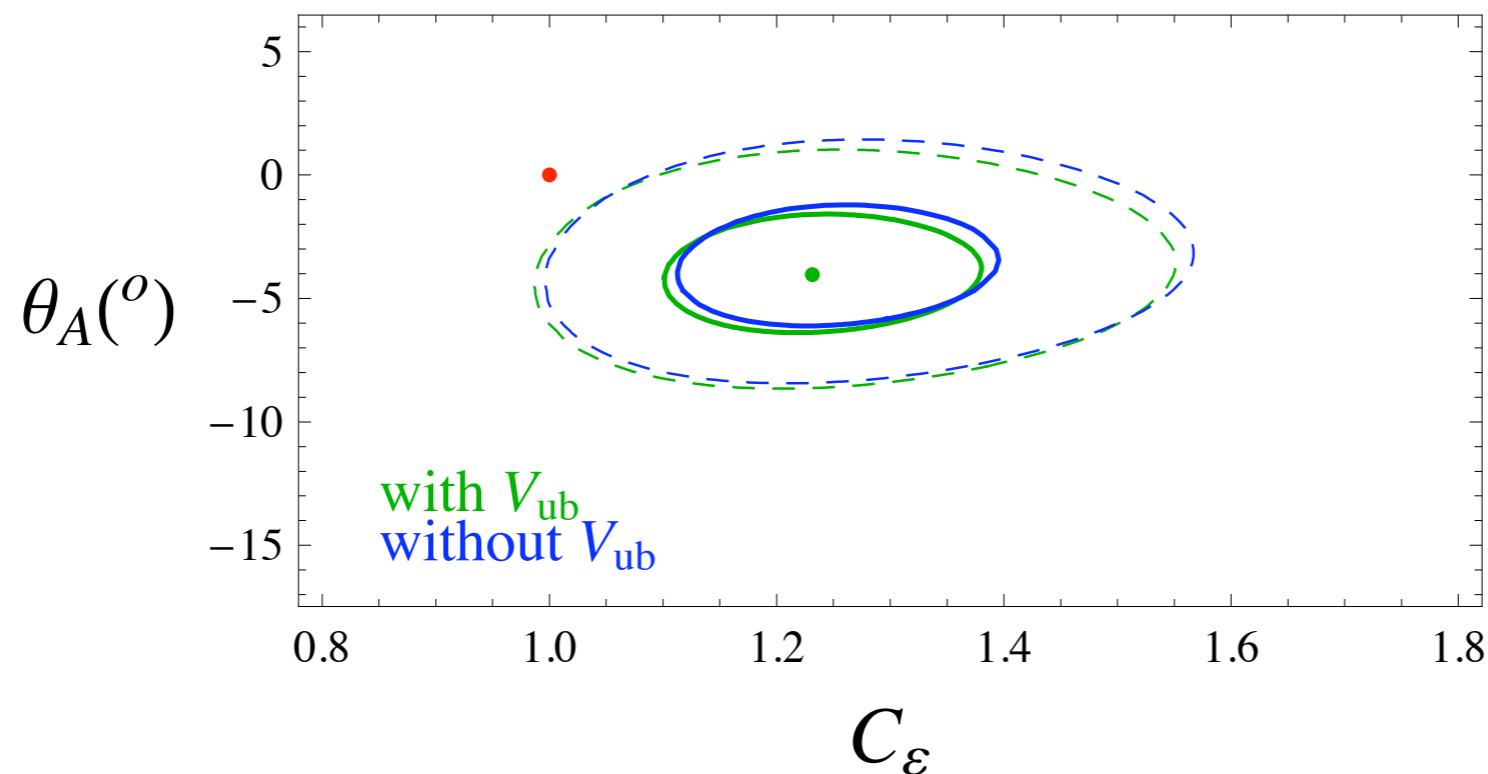
- Assume  $C_\varepsilon = 1$



- Comparison:  $\phi_d = \begin{cases} (-7.3 \pm 4.3)^{\circ} & \text{without } V_{ub} \\ (-2.0 \pm 11.6)^{\circ} & \text{with } V_{ub} \end{cases}$   
 $\theta_A = (-3.6 \pm 2.5)^{\circ}$

# Model Independent Analysis: $K$

- Alternative solution to the stress in the UT fit is NP in  $\varepsilon_K$   
[Buras, Guadagnoli]
- A new phase in penguin amplitudes ( $\theta_A$ ) is still required
- Assuming  $\phi_d = 0$  we find:



$$C_\varepsilon = 1.24 \pm 0.14$$

$$\theta_A = (-3.9 \pm 2.4)^\circ$$

# Correlation with other observables

- Proper treatment of new physics effects in penguin amplitudes is better implemented with NP contributions to the *QCD* and *EW penguin* operators
- Correlation between the  $b \rightarrow s\bar{s}s$  and  $K\pi$  asymmetries:

$$A_{CP}(B^- \rightarrow K^- \pi^0) - A_{CP}(\bar{B}^0 \rightarrow K^- \pi^+) = \begin{cases} (14.8 \pm 2.8) \% & \text{exp} \\ (2.2 \pm 2.4) \% & \text{QCDF} \end{cases}$$

- QCDF result very stable under variation of all the inputs
- Possible issue with large color suppressed contributions to the  $K^- \pi^0$  final state

# Operator Level Analysis: $b \rightarrow s$ amplitudes

- Effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left( \sum_{i=1}^6 C_i(\mu) O_i(\mu) + \sum_{i=3}^6 C_{iQ}(\mu) O_i(\mu) \right)$$

$$Q_4 = (\bar{s}_L \gamma^\mu T^a b_L) \sum_q (\bar{q} \gamma_\mu T^a q) \quad Q_{3Q} = (\bar{s}_L \gamma^\mu b_L) \sum_q Q_q (\bar{q} \gamma_\mu q)$$

likely to receive NP corrections

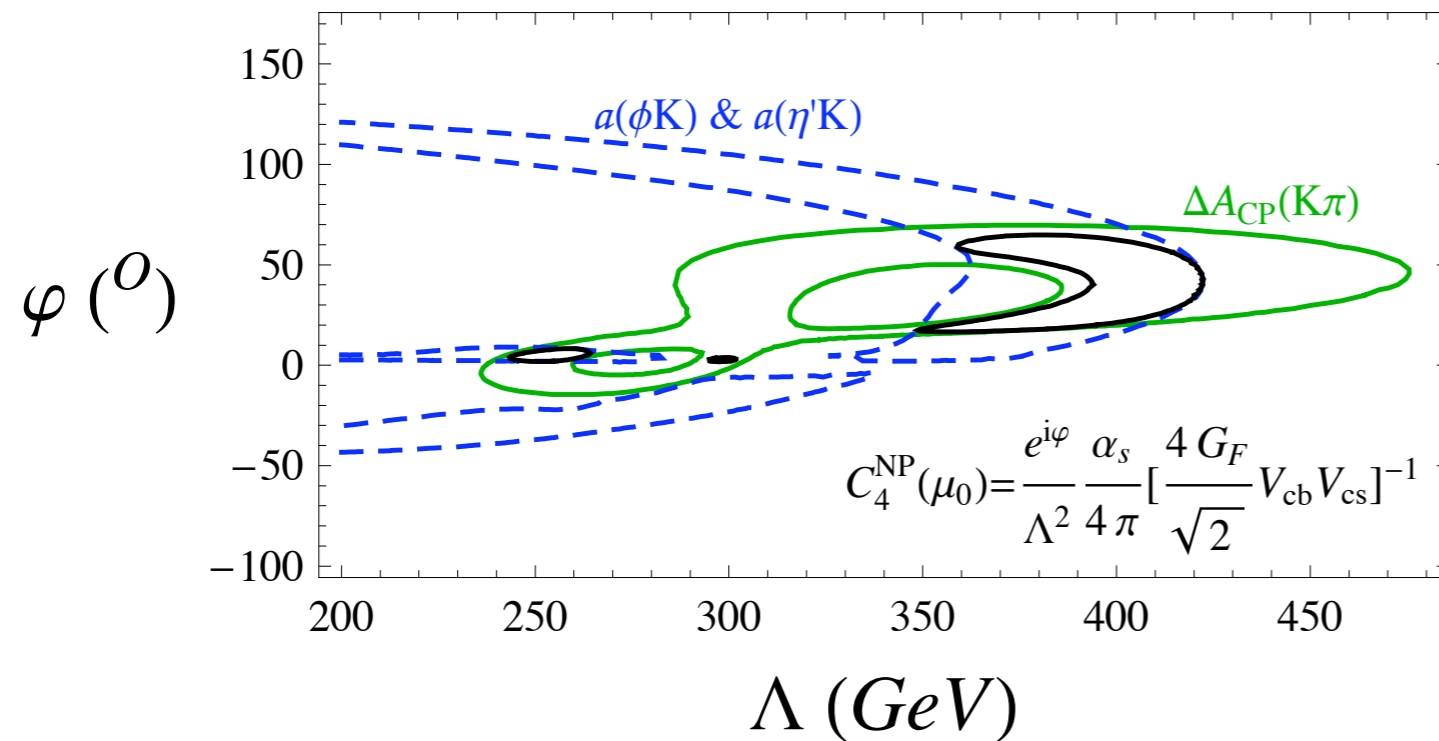
- Assume the following parametrization of NP effects:

$$\delta C_{4,3Q}(\mu_0) = \frac{\alpha_{s,e}}{4\pi} \frac{e^{i\varphi}}{\Lambda^2} \left[ \frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \right]^{-1}$$

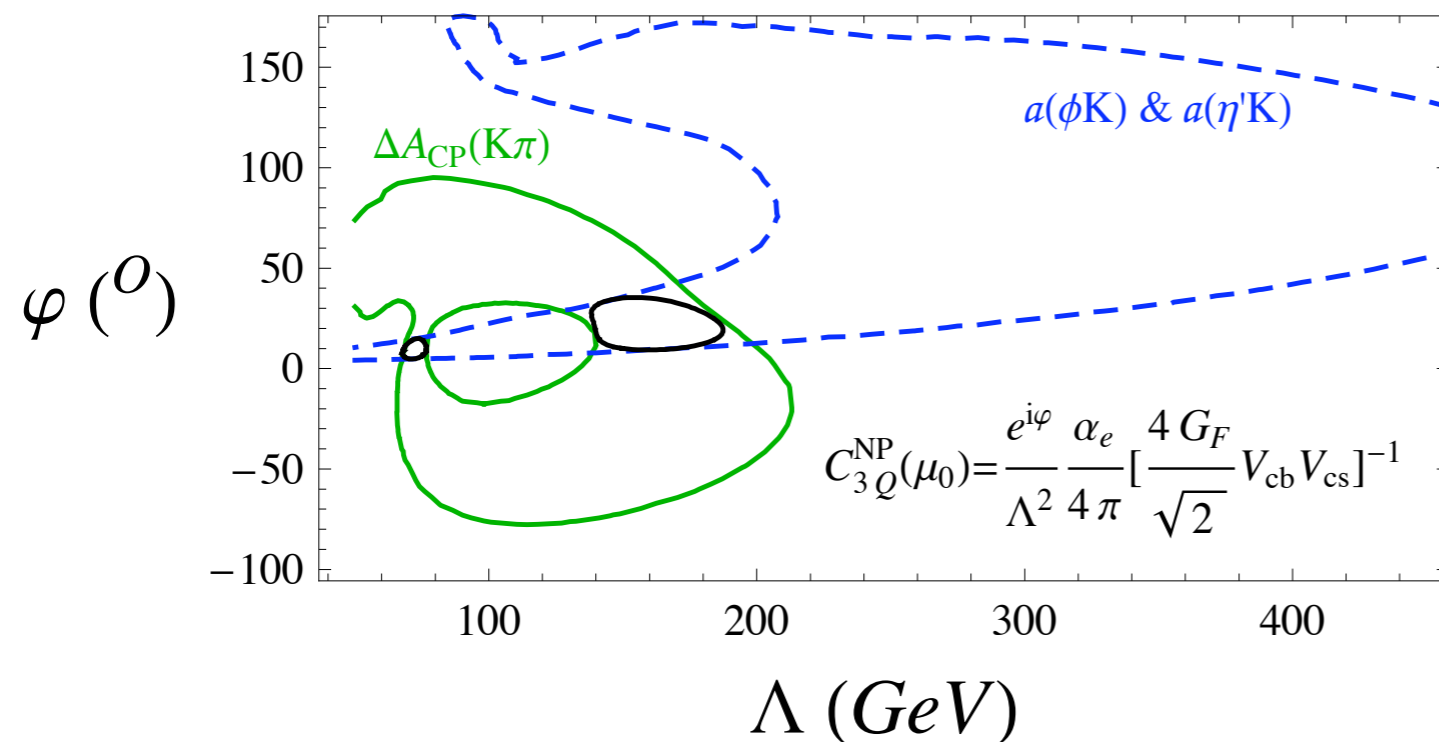
loop suppression + QED/QCD  
penguin  $g_{s,e}$  dependence

Effective mass scale that absorbs  
NP couplings

# Operator Level Analysis: $b \rightarrow s$ amplitudes



$$\Lambda \sim [350 \div 420] \text{ GeV}$$



$$\Lambda \sim [140 \div 190] \text{ GeV}$$

# Operator Level Analysis: *Mixing*

- Effective Hamiltonian for  $B_d$  mixing:

$$\mathcal{H}_{\text{eff}} = \frac{G_F^2 m_W^2}{16\pi^2} (V_{tb} V_{td}^*)^2 \left( \sum_{i=1}^5 C_i O_i + \sum_{i=1}^3 \tilde{C}_i \tilde{O}_i \right)$$

$$O_1 = (\bar{d}_L \gamma_\mu b_L) (\bar{d}_L \gamma_\mu b_L)$$

$$O_2 = (\bar{d}_R b_L) (\bar{d}_R b_L)$$

$$O_3 = (\bar{d}_R^\alpha b_L^\beta) (\bar{d}_R^\beta b_L^\alpha)$$

$$O_4 = (\bar{d}_R b_L) (\bar{d}_L b_R)$$

$$\tilde{O}_1 = (\bar{d}_R \gamma_\mu b_R) (\bar{d}_R \gamma_\mu b_R)$$

$$\tilde{O}_2 = (\bar{d}_L b_R) (\bar{d}_L b_R)$$

$$\tilde{O}_3 = (\bar{d}_L^\alpha b_R^\beta) (\bar{d}_L^\beta b_R^\alpha)$$

$$O_5 = (\bar{d}_R^\alpha b_L^\beta) (\bar{d}_L^\beta b_R^\alpha) .$$

- $B_s$  mixing ( $d \rightarrow s$ ),  $K$  mixing ( $b \rightarrow s$  &  $s \rightarrow d$ )
- Parametrization of New Physics effects:

$$\delta C_{1,4}^{B_q, K}(\mu_0) = \frac{1}{G_F^2 m_W^2} \frac{e^{i\varphi}}{\Lambda^2}$$

- Retain loop and CKM suppression

# Operator Level Analysis: *Mixing*

- The contribution of the LR operator  $O_4$  to  $K$  mixing is strongly enhanced ( $\mu_L \sim 2 \text{ GeV}$ ,  $\mu_H \sim m_t$ ):

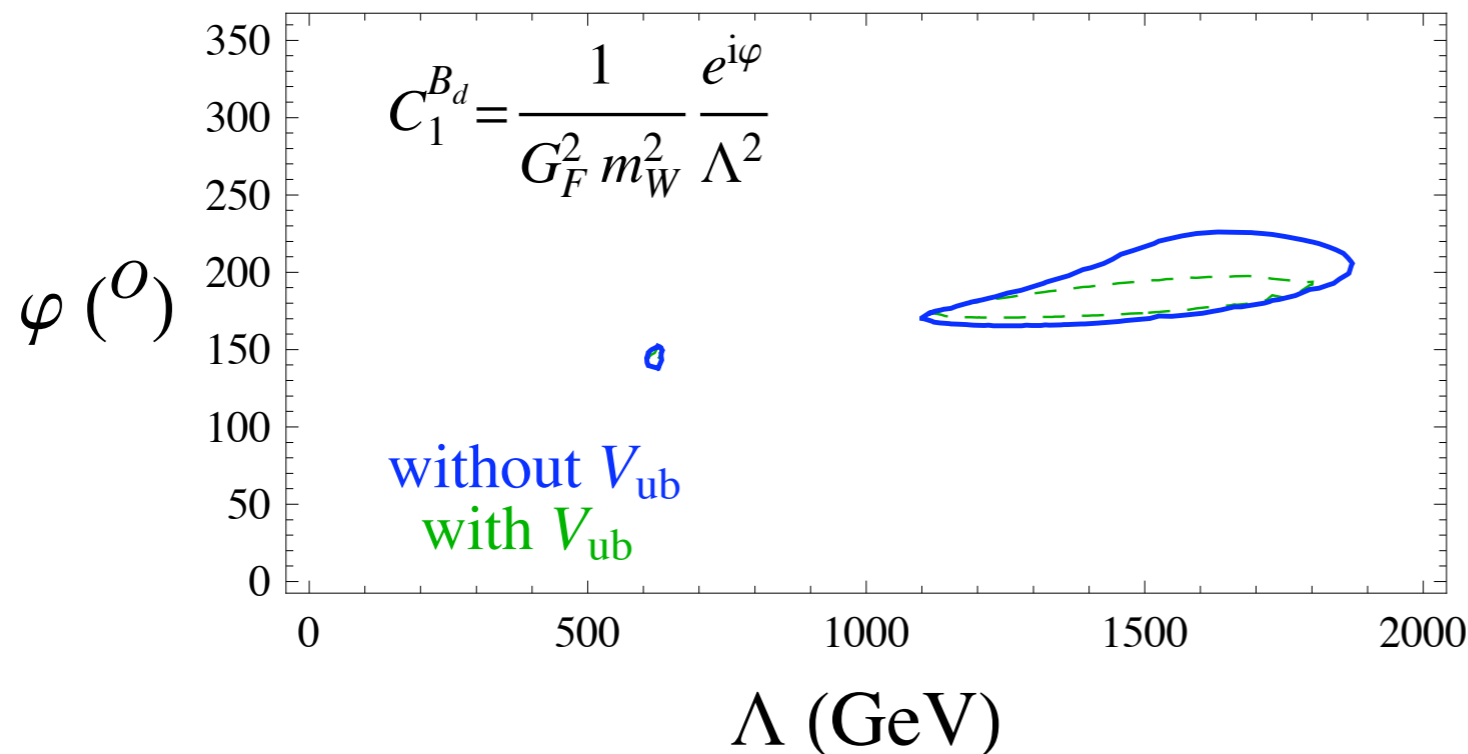
$$\begin{aligned}
 C_1(\mu_L) \langle K | O_1(\mu_L) | K \rangle &\simeq 0.8 C_1(\mu_H) \frac{1}{3} f_K^2 m_K B_1(\mu_L) \\
 C_4(\mu_L) \langle K | O_4(\mu_L) | K \rangle &\simeq 3.7 C_4(\mu_H) \frac{1}{4} \left( \frac{m_K}{m_s(\mu_L) + m_d(\mu_L)} \right)^2 f_K^2 m_K B_4(\mu_L)
 \end{aligned}$$

$$\frac{C_4(\mu_L) \langle K | O_4(\mu_L) | K \rangle}{C_1(\mu_L) \langle K | O_1(\mu_L) | K \rangle} \simeq (65 \pm 14) \frac{B_4(\mu_L)}{B_1(\mu_L)} \frac{C_4(\mu_H)}{C_1(\mu_H)}$$

- No analogous enhancement in  $B_q$  mixing

# Operator Level Analysis: $B_d$ Mixing

- New Physics in  $B_d$  mixing only:  $\delta C_1^{B_s} = \delta C_1^K = 0$
- Effects on  $a_{\psi K}$  and  $\Delta M_{B_s} / \Delta M_{B_d}$

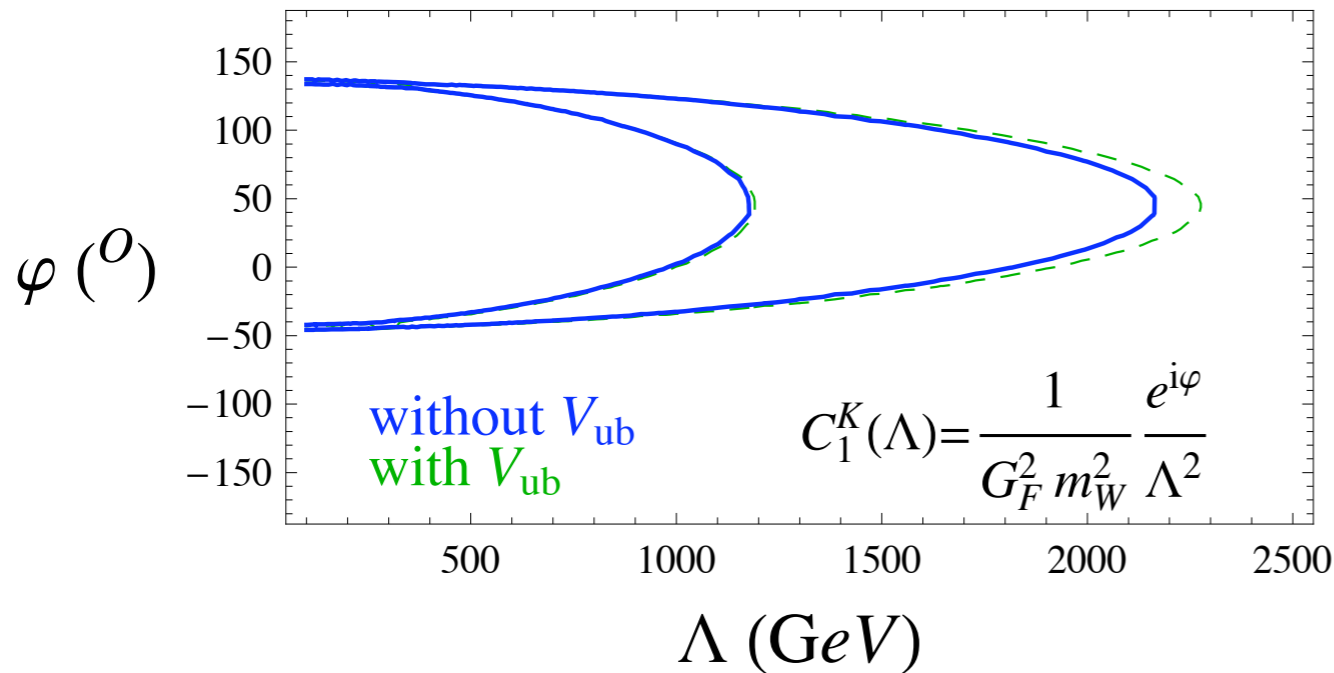


$$\Lambda \sim [1.1 \div 1.9] \text{ TeV}$$

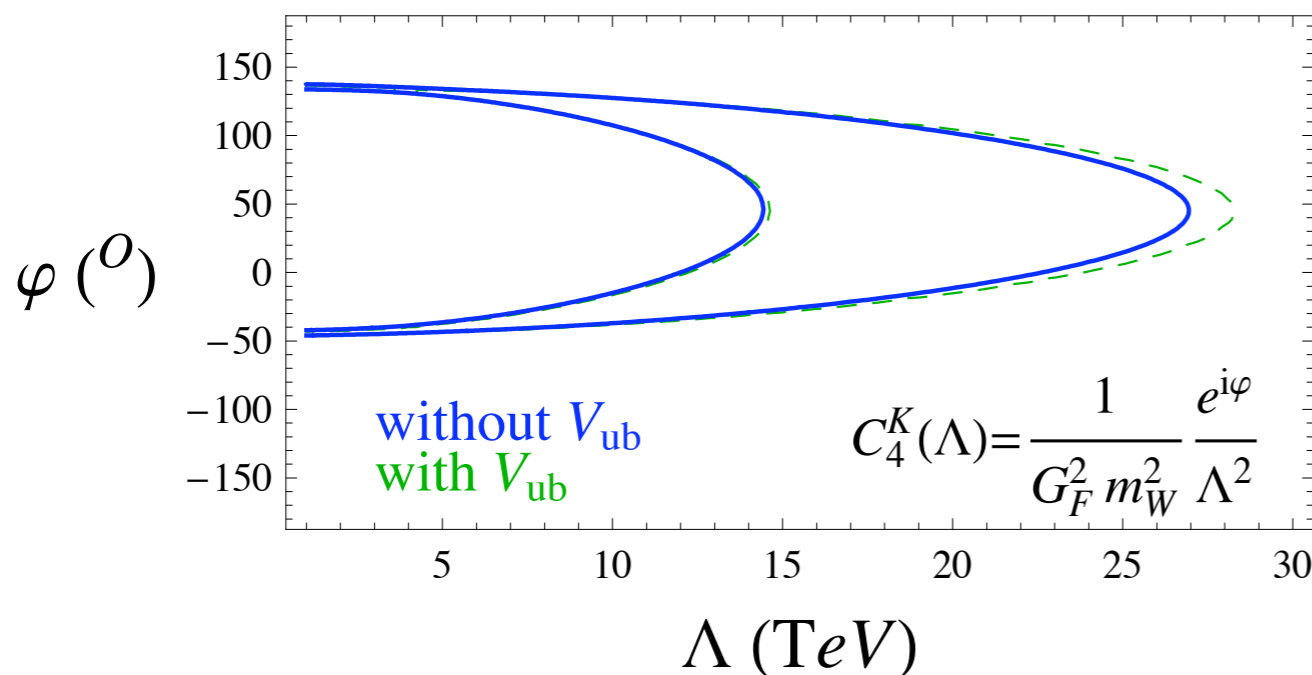
- Lower limit on  $\Lambda$  induced by  $\Delta M_{B_s} / \Delta M_{B_d}$

# Operator Level Analysis: $K$ Mixing

- New Physics in  $K$  mixing only:  $\delta C_1^{B_s} = \delta C_1^{B_d} = 0$



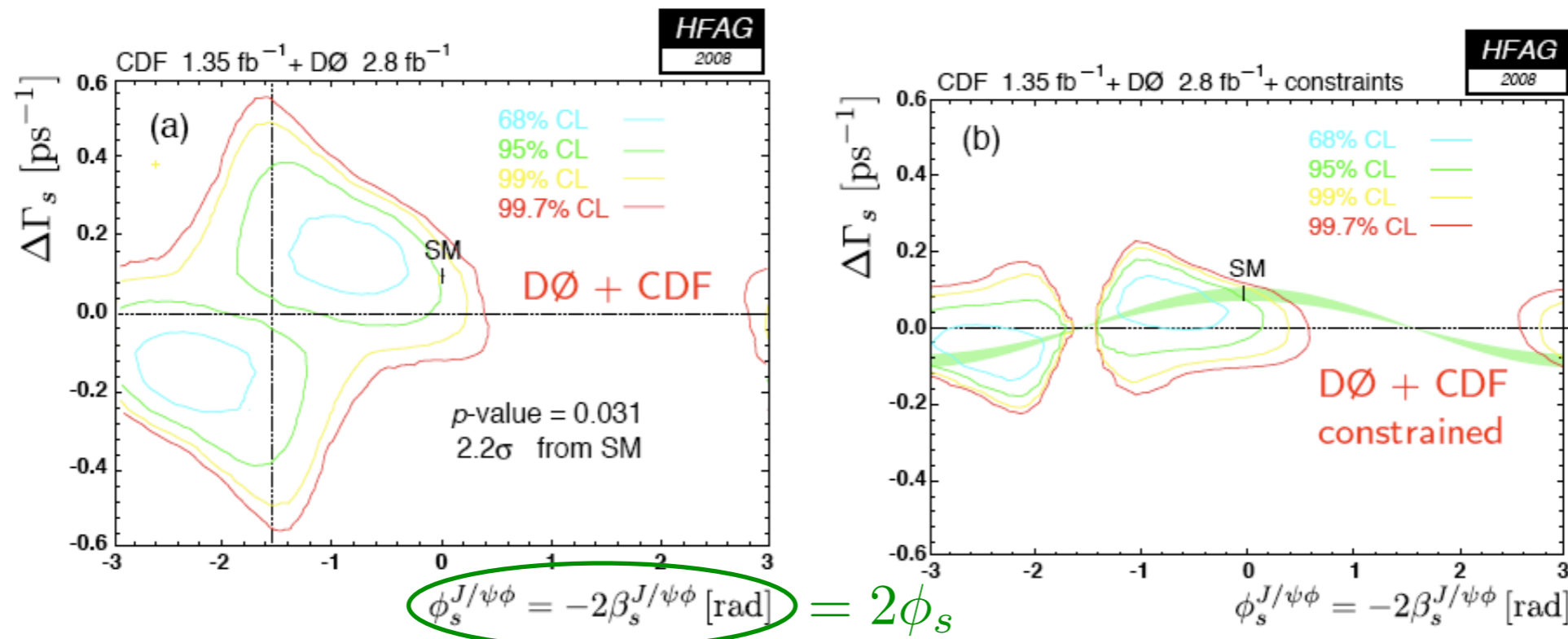
$$\Lambda \sim [1.2 \div 2.2] \text{ TeV}$$



$$\Lambda \sim [14 \div 27] \text{ TeV}$$

# Operator Level Analysis: $B_d$ and $B_s$ Mixing

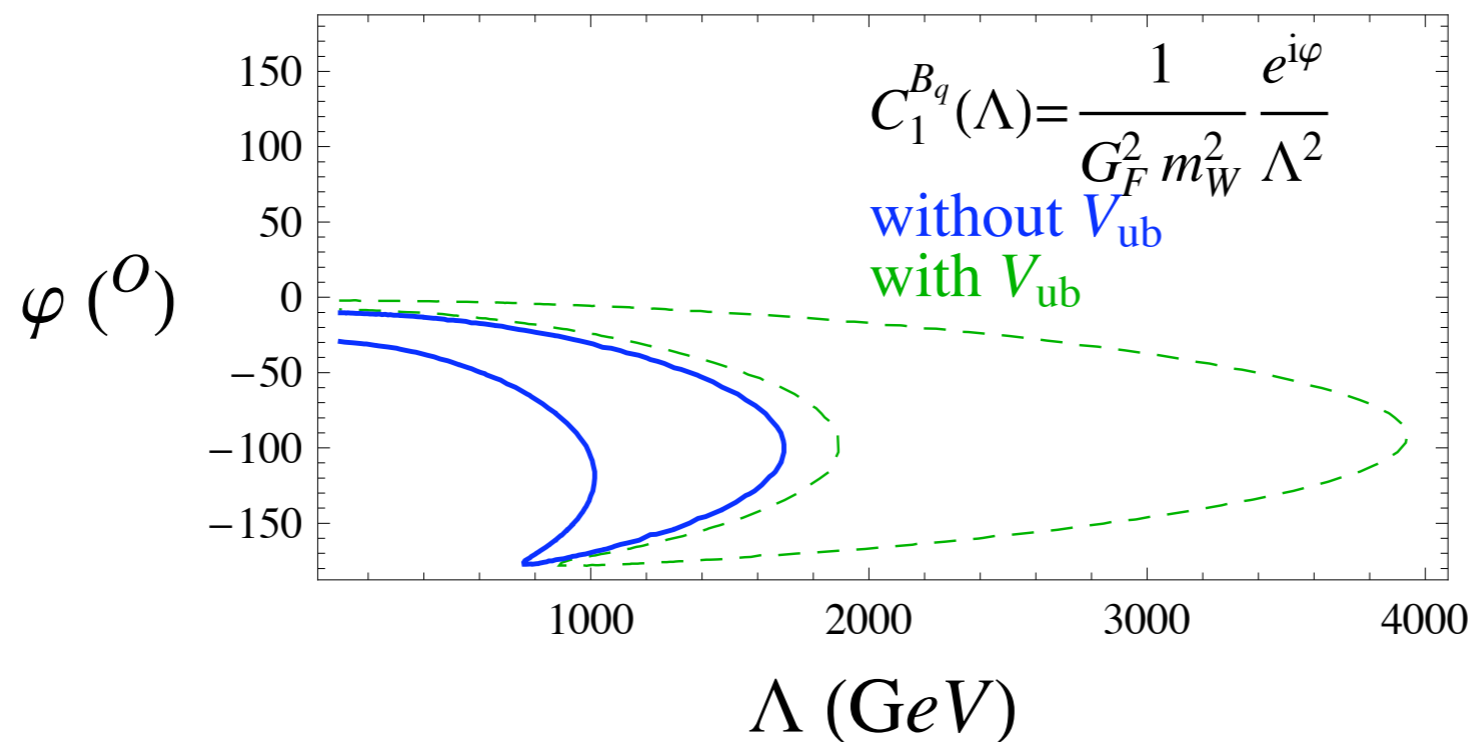
- Interesting possibility: *New Physics contributions to  $B_d$  and  $B_s$  mixing identical up to CKM factors*
- In our notation:  $\delta C_1^K = 0$  and  $\delta C_1^{B_s} = \delta C_1^{B_d}$
- New Physics in  $a_{\psi K}$  and  $a_{\psi \phi}$  ( $\Delta M_{B_s} / \Delta M_{B_d}$  unaffected)



- HFAG:  $\phi_s = -(22 \pm 10)^\circ \cup -(68 \pm 10)^\circ$

# Operator Level Analysis: $B_d$ and $B_s$ Mixing

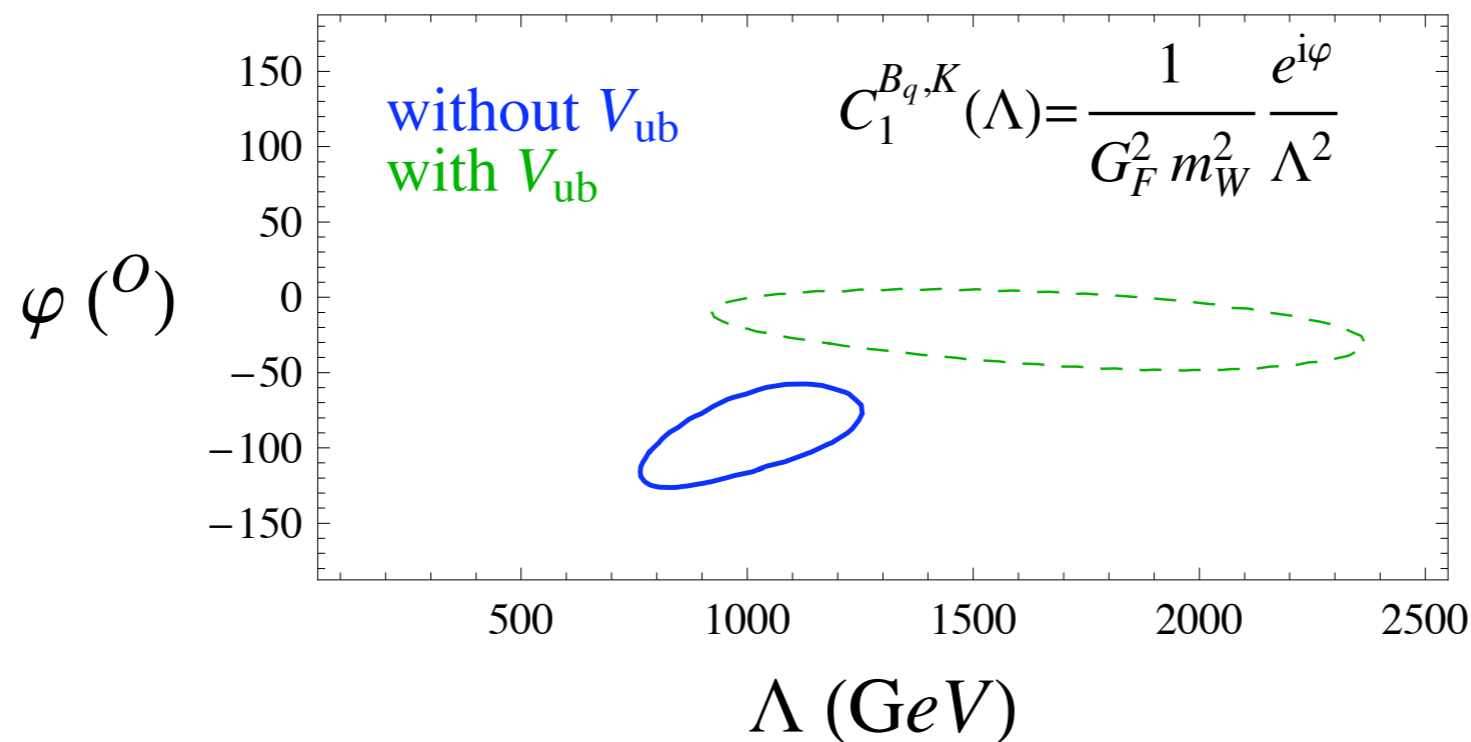
- In our notation:  $\delta C_1^K = 0$  and  $\delta C_1^{B_s} = \delta C_1^{B_d}$
- New Physics in  $a_{\psi K}$  and  $a_{\psi \phi}$  ( $\Delta M_{B_s} / \Delta M_{B_d}$  unaffected)



$$\Lambda \sim \begin{cases} [0.9 \div 1.7] \text{ TeV} & \text{without } V_{ub} \\ [1.8 \div 3.9] \text{ TeV} & \text{with } V_{ub} \end{cases}$$

# Operator Level Analysis: $B_d$ , $B_s$ and $K$ Mixing

- Simultaneous effects in  $B_d$ ,  $B_s$  and  $K$  mixing weighted by the respective CKM angles:  $\delta C_1^{B_s} = \delta C_1^{B_d} = \delta C_1^K$



$$\Lambda \sim \begin{cases} [0.8 \div 1.3] \text{ TeV} & \text{without } V_{ub} \\ [0.9 \div 2.4] \text{ TeV} & \text{with } V_{ub} \end{cases}$$

# Conclusions

- Thanks to the significantly improved accuracy in  $B_K$  [RBC +UKQCD, PRL'08],  $V_{ub}$  needs not to be used to get a meaningful constraint on  $\sin(2\beta)$
- Tension in the UT fit hints to NP in the flavor sector:
  - new phase in *penguin  $b \rightarrow s$  amplitudes* and in  *$B_d/K$  mixing*
- Correlation with NP signals in  *$B_s$  mixing* and in the  *$K\pi$  system*
- Typical *upper bounds* on NP scales are in the TeV range:

	$\Lambda$
$b \rightarrow s$ amplitudes	$O_4$ : [350÷420] GeV $O_{3Q}$ : [140÷190] GeV
$B_d$ mixing	[1.1÷1.9] TeV
K mixing	LL: [1.2÷2.2] TeV    LR: [14÷27] TeV
$B_d=B_s$ mixing	[0.9÷1.7] TeV
$B_d=B_s=K$ mixing	[0.8÷1.3] TeV

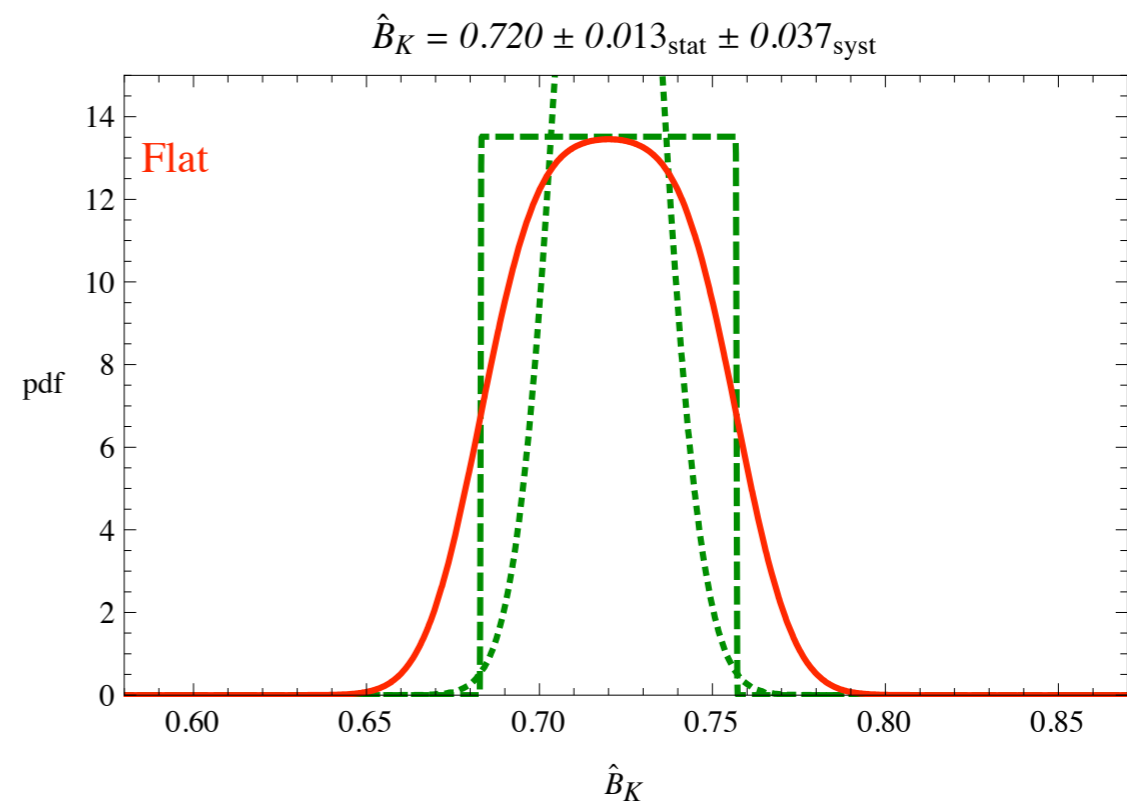
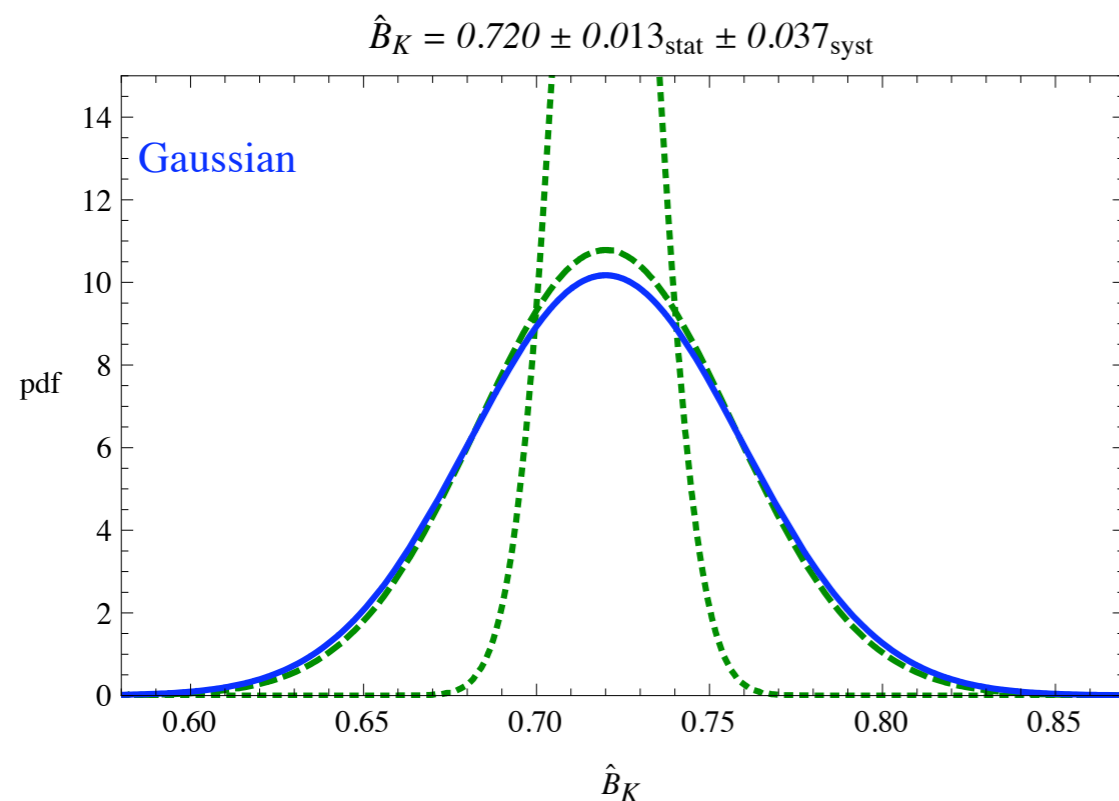
*Backup Slides*

# Comments on systematic uncertainties

- We treat all systematic uncertainties as gaussian
- Most relevant systematic errors come from lattice QCD ( $B_K, \xi$ ) and are obtained by adding in quadrature several different sources of uncertainty
- Gaussian treatment seems a fairly conservative choice

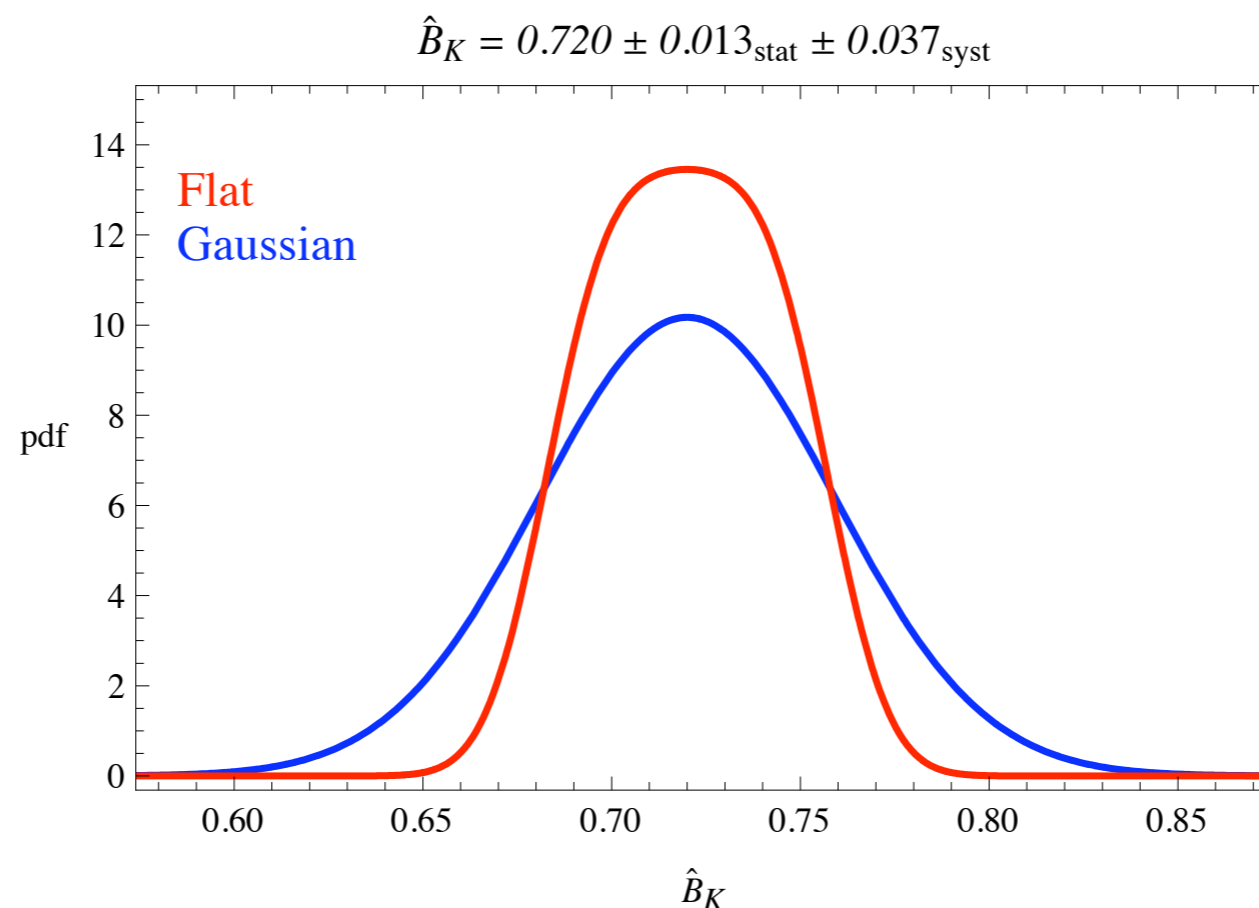
# Comments on systematic uncertainties

- We treat all systematic uncertainties as gaussian
- Most relevant systematic errors come from lattice QCD ( $B_K, \xi$ ) and are obtained by adding in quadrature several different sources of uncertainty
- Gaussian treatment seems a fairly conservative choice



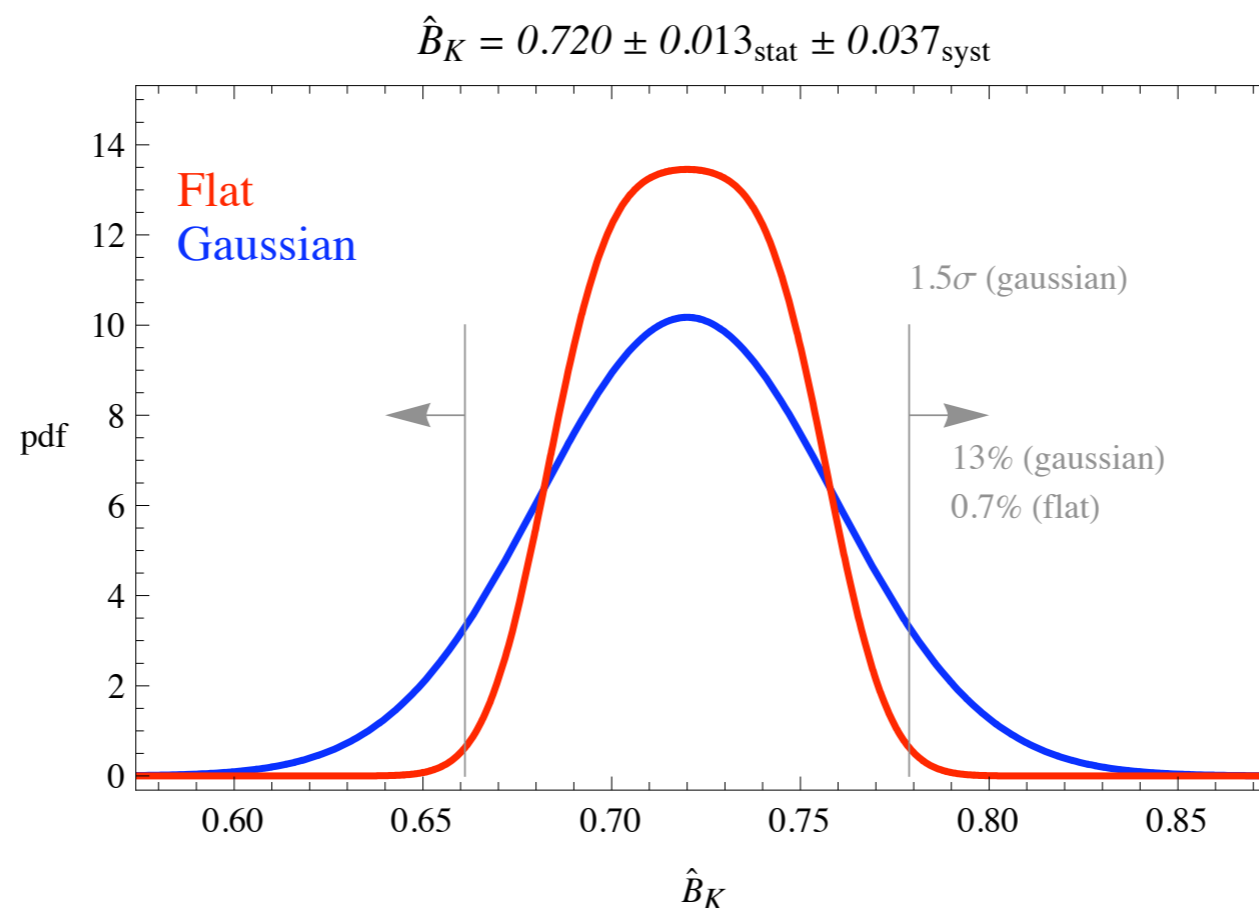
# Comments on systematic uncertainties

- We treat all systematic uncertainties as gaussian
- Most relevant systematic errors come from lattice QCD ( $B_K, \xi$ ) and are obtained by adding in quadrature several different sources of uncertainty
- Gaussian treatment seems a fairly conservative choice



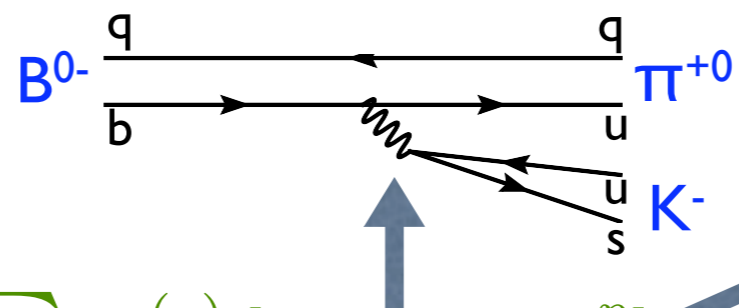
# Comments on systematic uncertainties

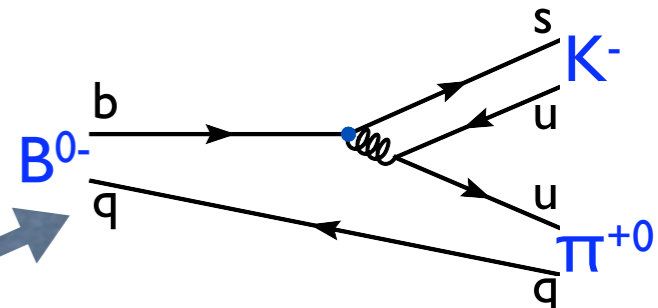
- We treat all systematic uncertainties as gaussian
- Most relevant systematic errors come from lattice QCD ( $B_K, \xi$ ) and are obtained by adding in quadrature several different sources of uncertainty
- Gaussian treatment seems a fairly conservative choice



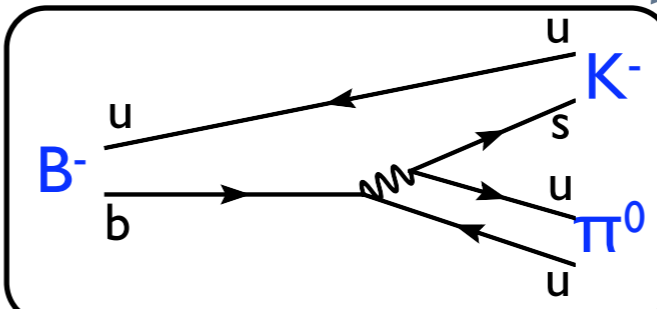
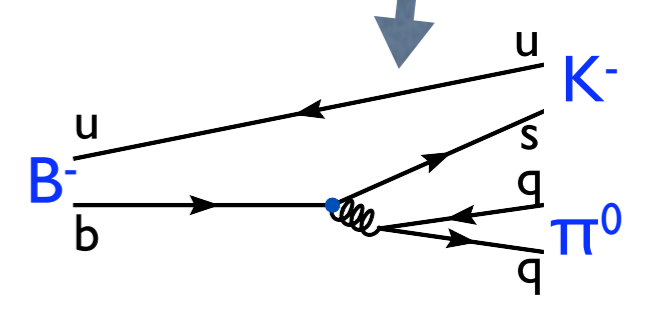
# CP asymmetries in $B \rightarrow K\pi$

- Amplitudes in QCD factorization:

$$\mathcal{A}_{\bar{B}^0 \rightarrow \pi^+ K^-} = A_{\pi \bar{K}} \sum_{p=u,c} \lambda_p^{(s)} [\delta_{pu} \alpha_1 + \hat{\alpha}_4^p]$$


$$\sqrt{2} \mathcal{A}_{B^- \rightarrow \pi^0 K^-} = \mathcal{A}_{\bar{B}^0 \rightarrow \pi^+ K^-} + A_{\bar{K} \pi} \sum_{p=u,c} \lambda_p^{(s)} \left[ \delta_{pu} \alpha_2 + \delta_{pc} \frac{3}{2} \alpha_{3,EW}^c \right]$$


color suppressed [Gronau, Rosner]

- NP contributions to the QCD and EW penguin